Photon-Recycling for High Brightness LEDs

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A novel LED "recycles" the photons emitted by a short wavelength active region to produce a second, longer wavelength emission, which can be combined to generate white light without the use of phosphors. The addition of a third active-region makes a white emitter with good color rendering properties. With theoretical efficiencies in excess of 300 lm/W, photon-recycling LEDs are contenders for signs and future general illumination applications.

LEDs have long since become ubiquitous in their role as humble status indicators for domestic and industrial appliances. However, in the last ten years, the emergence of blue and violet emitters from the development of GaN, AlGaN, and InGaN materials [1] and improvements in efficiencies have led to high brightness LEDs suitable for a range of indoor and outdoor applications [2].

These devices have a significant advantage compared to conventional light sources: ideal LEDs can have internal quantum efficiencies approaching 100 %, where nearly every injected electron generates a photon. However, this is a figure of merit mainly of interest to device engineers. The efficiency or luminous performance, on the other hand, is a measure of the brightness of white light sources as it is perceived by the human eye. It is measured in lumens per Watt (lm/W).

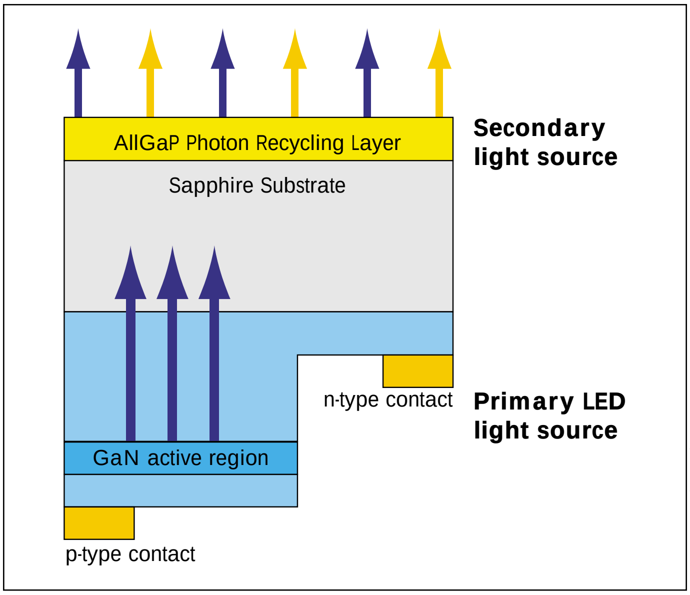

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Figure 1. Structure of the photon-recycling semiconductor (PRS) LED. The device consists of the primary active region emitting in the blue wavelength range and an electrically-inactive photon recycling wafer re-emitting a complementary color such as yellow/orange.

In terms of their luminous performance, LEDs can achieve theoretical efficiencies exceeding 300 lm/W. This is not the case for incandescent light sources such as conventional light bulbs, which have typical efficiencies of only 15-20 lm/W. This is due to the fact that incandescent lamps emit mostly in the infrared where the eye is insensitive.

Fluorescent light sources exhibit a higher efficiency - around 60 lm/W. This is, however, limited by the fact that the gas discharge inside the lamp occurs in the UV, and considerable energy is lost during down-conversion to the visible region by the phosphor coating on the inside of the fluorescent tube. In comparison, the LED's ability to emit very efficiently makes it the light source of the future. And the race is now on to develop semiconductor-based light sources suitable for general purpose lighting applications, including white and colored light.

The high efficiency of LEDs means that the potential exists for enormous energy savings. It is estimated that about 30 % of all electrical power generated is used for lighting. If the energy savings promised by LEDs could be realized, calculations predict that no new power plants would need to be built during the next 20 years. Since much of the electrical power is generated using oil-consuming power plants, it is clear that the dependence on this finite resource could be substantially reduced if efficient LEDs could replace power-hungry incandescent light sources.

The Approach to General Illumination

A conventional LED emits close to monochromatic light, and the number of possible colors is limited. Many approaches

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** 8, Saint Mary's Street, Boston, MA 02215, USA. Tel: +1 617 353 1910; Fax: +1 617 353-6440; Email: FSchubert@bu.edu* exist that transform this narrow spectrum into one recognizable as white light. White can be generated in LEDs through the use of a phosphor film, either by coating the device or the plastic encapsulant [1]. The phosphor, which is optically excited by a semiconductor LED, emits over a broad range of wavelengths, resulting in the appearance of white light. However, the deposition of the phosphor increases the manufacturing cost of white emitters compared to conventional monochromatic LEDs.

White light emission can also be achieved by mixing the outputs of three discrete LEDs emitting in the red, green, and blue range of the visible spectrum, such as frequently used for full-color displays. Again, the fabrication of a white-light source using three LEDs is more expensive compared to the single-chip approach, making this solution inappropriate for low-cost general illumination applications.

Yet another approach uses organic dye molecules to convert the short-wavelength light to a longer wavelength. However, under long-term optical irradiation, the efficiency of organic dye molecules, which lack the long-term stability provided by semiconductors, degrades. White light LEDs can also be made from polymers. These exhibit much lower electrical conductivity than either metals or semiconductors, and as a result, cannot be subjected to high electrical current densities. This limits their use to lower-brightness applications such as displays rather than high intensity light sources.

Therefore, device designs that are capable of fully exploiting the potential of high brightness LEDs are currently being sought to devise energy-efficient sources for general illumination and other applications. Here we discuss a novel concept for an LED based on a 'photon-recycling semiconductor' LED, or PRS-LED. This device represents an all-semiconductor approach to white light emission, and can produce either white light or a range of colors with theoretical efficiencies in excess of 300 lm/W.

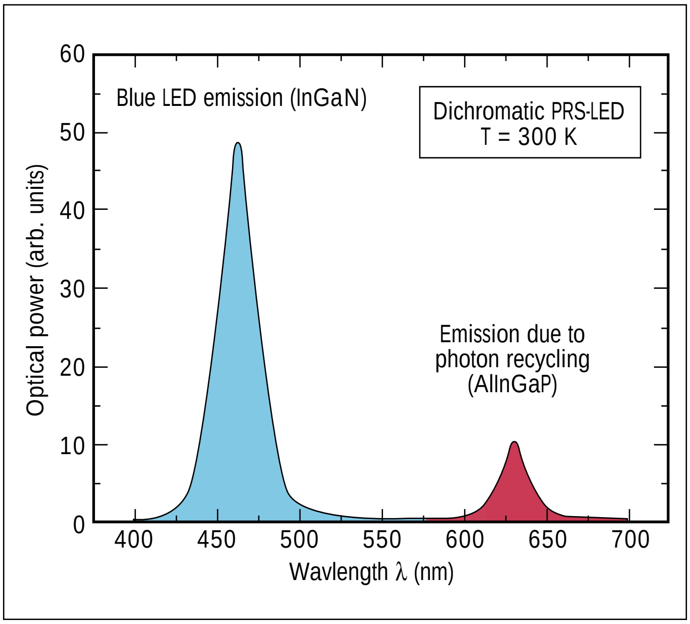

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Figure 2. The emission spectrum of a PRS-LED consists of a primary peak from GaN/InGaN at 470 nm and a secondary emission peak from AlInGaP at 625 nm.

The Photon Recycling LED

The first PRS-LED was demonstrated as a hybrid device by Guo and colleagues in 1999 [3]. This device consisted of an epitaxially-grown InGaN-based blue LED bonded to a second wafer containing an AlGaInP active region. The device thus emits two or more discrete wavelengths, and the combined output is perceived as white light. The PRS-LED can also be designed to emit a multitude of other colors, which is not possible with conventional LEDs. In addition, more recycling layers are possible, giving rise to bi- and trichromatic PRS-LEDs.

We first discuss the 'dichromatic' PRS-LED, which emits two discrete wavelengths. The device structure is shown in Figure 1. It consists of a primary and a secondary light source. The primary light source is an GaN/InGaN LED grown on a transparent sapphire substrate, designed to emit in the blue spectral range. The InGaN/GaN LED measures 600 x 600 µm and employs 50 nm-thick Al and Ni for the *n*- and *p*-type contacts, respectively. Electroluminescence is generated in the active region by current injection. The primary wavelength is centered around 470 nm.

For the secondary source, the PRS-LED employs an AlGaInP active region wafer-bonded to the sapphire substrate of the primary emitter. The GaAs substrate of the AlInGaP is removed by chemically-assisted polishing and selective wet etching to reduce further losses in efficiency due to absorption. In

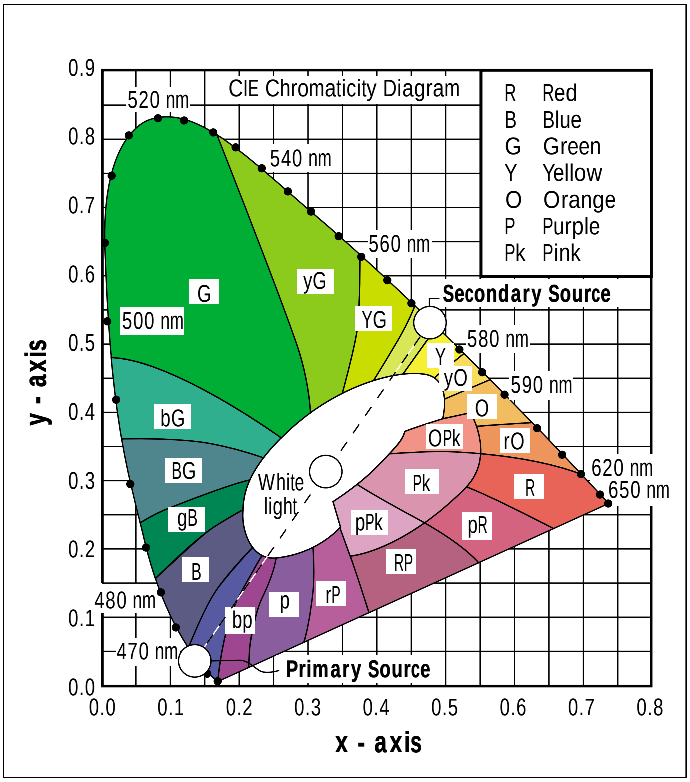

Figure 3. Illustration of different colors on the chromaticity diagram. White light is located in the center. The PRS-LED generates white light using two monochromatic colors - the primary and secondary light source – shown here located on the perimeter of the chromaticity diagram (after: Commission Internationale de l'Eclairage, CIE).

operation, some of the photons emitted by the primary light source are absorbed by the AlInGaP region and re-emitted (or recycled) as light at a longer wavelength. If these are complementary wavelengths and the two light sources have the correct power ratio, then the light appears white to the observer. Hundreds of other colors can be generated if the two light-emitting regions emit two non-complementary colors. In theory, it is possible to generate any color with the PRS-LED [3, 4].

The PRS-LED can also be monolithically integrated by employing InGaN with two different indium mole fractions for both the primary and secondary active regions, and growing the two active regions during the same growth run. InGaN has been shown to be suitable for emission up to the yellow range of the optical spectrum, and a white, a light blue, a whitish green and a light blue-green should all be feasible. No additional light-emitting materials - phosphors, dyes or semiconductor layers - are required to generate white light. The monolithic approach could allow lower manufacturing costs compared to other semiconductor-based white-light emitters.

Chromaticity Considerations

The emission spectrum of a prototype PRS-LED is shown in Figure 2. The emission of the primary LED occurs in the blue region of the visible spectrum (noted above), and a secondary emission line occurs in the red region, located at 625 nm. The two wavelengths can be chosen by selecting the composition of the active layers of the primary and secondary light emitters. The thickness of the secondary active region determines how much light is absorbed and allows one to obtain the required power ratio between the two emission lines to produce white light. The emission of the photon recycling device appears to be “perfect” white to the beholder.

The generation of different colors can also be understood in terms of the CIE chromaticity diagram shown in Figure 3. Monochromatic colors are located on the perimeter of the chromaticity diagram, and the wavelengths of these monochromatic sources are indicated. Colors in the middle of the chromaticity diagram can be obtained by superimposing several monochromatic sources.

As an example, Figure 3 shows a monochromatic primary color located in the blue wavelength range and a monochromatic secondary color located near the greenish-yellow range. The binary complementary mixing of these two monochromatic colors allows access to the center of the chromaticity diagram, i.e. it allows the generation of white light [4].

Efficiency and Color Rendering

The sensitivity spectrum of the human eye, which has a maximum in the green wavelength range at 555 nm, is shown in Figure 4. The eye’s sensitivity strongly decreases in the red and the violet and has essentially zero sensitivity for wavelengths <390 nm and >750 nm. Thus, light sources operating near this maximum in the green wavelength region have the highest luminous performance. The PRS-LED takes advantage of this: allowing for the energy loss occurring during the recycling process, a very high luminous performance of 330 lm/W is theoretically obtained. The ability to exactly design the two (or even three) wavelengths of the device allows one to attain the maximum performance from a white light emitter.

Color rendering is another important property of white light sources. This quantity describes how objects illuminated by a light source are perceived. Most white and off-white illuminants for typical reflecting surfaces feature a relatively high color rendering index (CRI) i.e. > 50. On the other hand, mercury vapor lamps and high pressure sodium lamps have CRIs around 20, causing some surfaces to appear odd in certain circumstances – this is often tolerated to take advantage of high luminous efficiency. In the case of the dichromatic PRS-LED, the CRI is much lower than that of typical lamps such as incandescent and fluorescent light sources. This makes it well-suited for indicator light applications but less amenable to illumination applications.

However, by adding a second photon-recycling active region, a ‘trichromatic’ LED can be fabricated. The CRI of the trichromatic device, at around 60, is comparable to conventional light sources. At 290 lm/W, the theoretical luminous performance of the trichromatic PRS-LED is still very high, preserving the efficiency advantage of this device compared to other light sources. Thus, the color rendering properties of the PRS-LED can be optimized for different applications.

Another important advantage of the modified LED relates to design of broad-spectrum white light sources that simulate sunlight. White sunlight is distributed over the entire visible spectrum, i.e. a high light intensity is emitted by the sun even at the edges of the visible spectrum, where the eye is insensitive. In

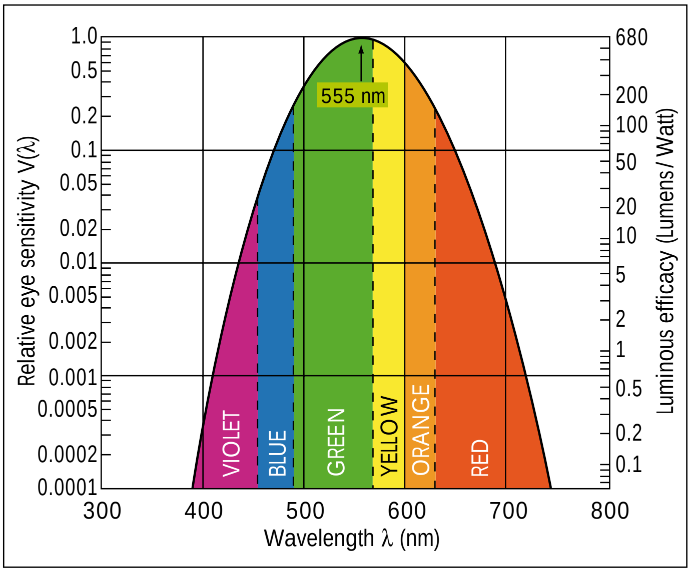

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Figure 4. The sensitivity of the human eye is a maximum at 555 nm in the green wavelength range. There are only three types of color-sensitive receptors in the eye, which means that white light can be perceived from the complimentary mixing of as few as two separate wavelengths. With its use of just two complimentary wavelengths positioned well inside the eye’s spectral envelope, the PRS-LED produces white light very efficiently.

designing white light generators, the close reproduction of the sun's spectrum is not an efficient way to produce white light. The PRS-LED takes a fundamentally different approach. In this device, several monochromatic light emitters are positioned at wavelengths chosen such that the emission results in the highest possible luminous performance.

How the PRS-LED Efficiency Compares

Tungsten filament and halogen incandescent light sources have a luminous efficiency of 15-25 lm/W. Fluorescent tubes and the newer compact fluorescent light bulbs have a luminous performance of about 60 lm/W. In comparison, the calculated theoretical efficiency of the dichromatic PRS-LED is around 330 lm/W, which is much higher than that of conventional light sources. Even if only 50 % of the PRS-LED's efficiency, i.e. about 160 lm/W, can be demonstrated within the next 5 years, this LED would significantly outperform conventional light sources. At the present time, the PRS-LED has a luminous performance of less than 10 lm/W.

As mentioned above, other technical approaches to making white LEDs exist, including diodes based on phosphor (similar to fluorescent light) and also light-emitting polymers. However, the maximum theoretical luminous efficiency of phosphor-based white LEDs is 280 lm/W, lower than the efficiency of the dichromatic PRS-LED. Polymer LEDs are not expected to be suitable for high-brightness light emission due to their inherently high electrical resistivity.

Potential Applications

The PRS-LED has many possible applications. In terms of device flexibility, the dichromatic PRS diode should be well-suited for signage, display, and some illumination applications. The trichromatic device is also applicable to high-quality illumination due to the higher CRI afforded by its three emission wavelengths.

The device can also be customized for different applications: the illumination of streets requires excellent efficiency but color rendering has little relevance. On the other hand, the illumination of artwork in a museum requires excellent color rendering, while the efficiency is of little importance. A big advantage of the PRS-LED is that it can allow the properties for the type and quality of white light produced to be tailored.

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